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HYDRAULIC EXTRUSION

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

DEPARTMENT OF MECHANICAL ENGINEERING

by

DAVID R. BUDNEY, B.Sc. (Alberta)

EDMONTON, ALBERTA

SEPTEMBER, 1965

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UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled " Hydraulic Extrusion" submitted by David R. Budney in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

The purpose of the experimental work of this thesis is to investigate the relationship between the reduction and the extrusion pressure for the process of hydraulic extrusion. The effect of the lubricating properties of the fluid is considered. A comparison of the extrusion pressures and deformation efficiencies is made between the processes of hydraulic extrusion and inverted mechanical extrusion.

The metal used in the experiments was 0.065 per cent tellurium lead in both the work-hardened and annealed states. Thirty degree and forty-five degree semi-angle dies were used for these experiments.

It was found that extrusion through a forty-five degree semi-angle die required a higher extrusion pressure than extrusion through a thirty degree semi-angle die. It was found that lubrication for hydraulic extrusion was not as good as intuitively expected.

An appendix is included indicating progress of the development of explosive hydrodynamic extrusion apparatus.

ACKNOWLEDGMENTS

The author wishes to extend his appreciation to Dr. J.B. Haddow for supervising this thesis.

He would also like to thank the National Research Council and the University of Alberta for providing the financial assistance which made his graduate studies possible.

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CHAPTER I

INTRODUCTION

The metal forming processes of hydraulic extrusion and inverted mechanical extrusion were investigated experimentally to determine the degree to which the fluid used in the hydraulic extrusion process aids in reducing die friction. It was also desired to obtain relationships between fluid pressure and percentage reduction of billet area for annealed and fully hardened tellurium lead for the process of hydraulic extrusion.

The first experimental investigations of hydraulic extrusion were probably conducted by Bridgman (1), who discontinued his work after observing intermittent and violent discharge of the extruded product. Since that time, Gunn, Green and Pugh (2, 3, 4) succeeded in extruding a brittle material into a high pressure fluid, using the previously known fact that material becomes more ductile under the influence of hydrostatic pressure. In 1963, Beresnev (5) dealt with the importance of the properties of the fluid used for hydraulic extrusion. Cook, Fiorentino and Sabroff (6) advanced design features for the process in 1964.

1.1 Description of the Processes

Figure 1 shows the hydraulic extrusion apparatus used in the experiments. The cylindrical billet has a conical surface machined at the end which makes contact with the conical surface of the die. A film of grease acts as a seal between the die and die support. Grease is also used at the billet-die interface for both sealing and lubricating. After

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the billet is placed in the container, the container is filled with oil and the piston is inserted in the sleeve. Load is then applied to the piston. The oil transmits the applied load to the billet, forcing it through the die orifice, producing a cylindrical bar of reduced cross-sectional area. Contact is not made between the billet and container wall unless tipping of the billet occurs. If contact is made between the billet and container wall, movement of the billet is lubricated by the oil in the container.

The apparatus used for inverted mechanical extrusion is shown in figure 2. The die is advanced at a constant rate, forcing the metal through the die orifice, reducing the cross-sectional area of the cylindrical billet. Except for a portion of the billet near the die, which is undergoing deformation, there is no relative motion between the billet and container wall.

In both processes, unlike direct mechanical extrusion, friction losses at the surface of the undeformed billet are almost entirely eliminated.

1.2 Advantages and Disadvantages of the Hydraulic Extrusion Process

1.2.1 Advantages

(a) The elimination of friction between the billet and container wall permits the extrusion of billets having a high length: diameter ratio. Extrusion of long billets by inverted mechanical extrusion is more difficult, owing to the long load sleeve required.

(b) The expulsion of the entire billet eliminates the necessity of a discard.

(c) The presence of the extrusion fluid, which acts as a high pressure lubricant, may reduce billet-die friction.

1.2.2 Disadvantages

(a) The violence of the expulsion of the billet may damage the finished product.

(b) Reloading of billets is difficult, owing to the use of a fluid.

(c) Movement of the piston and billet in the same direction limits the length of the billet to be extruded. However, Green (7) shows that this difficulty can be overcome by having the pressurizing piston operate in a direction different from that of the movement of the billet.

1.3 Theoretical Considerations

If the Von Mises yield criterion is used, no exact mathematical solution for the extrusion pressure required for steady state axi-symmetric extrusion is available. This is because the governing equations for the axi-symmetric case are elliptic, unlike the plane strain problem where the governing equations are hyperbolic (8).

CHAPTER II

COMPARISON TO THE IDEAL PROCESS

2.1 The Use of the Average Yield Stress

It is assumed that for the ideal hydraulic extrusion process, the material is both isotropic and homogeneous before and after deformation. Using these assumptions, the effect of work-hardening on hydraulic extrusion may be introduced.

The current uni-axial yield stress $\bar{\sigma}$ for a particular element is assumed to be a function of the total plastic work per unit volume, W_p, performed on the element since the material was last in an annealed state. This is written as

$$\bar{\sigma} = F(W_p) \qquad \text{..............2.1}$$

For a non-hardening metal, $\bar{\sigma}$ is a constant and is equal to Y, the uni-axial yield stress. W_p is given in Cartesian Tensor notation by

$$W_p = \int \sigma_{ij} de_{ij}^{(p)} \qquad \text{..............2.2}$$

where σ_{ij} are the components of the stress tensor, and the integration is taken over the strain path, $e_{ij}^{(p)}$, of the element considered.

Taylor and Quinney (9) have shown that the Von Mises yield criterion is obeyed quite closely by lead, a ductile material. Consequently, the Mises yield criterion is used in this discussion.

Then, for a particular element

$$\frac{\sigma'_{ij}\sigma'_{ij}}{2} = k^2 = \frac{\bar{\sigma}^2}{3} \qquad \text{..............2.3}$$

where σ'_{ij} are the deviatoric components of the stress tensor at a point in the deforming body. k is the yield stress in pure shear.

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The generalized or equivalent plastic strain increment is defined as

$$d\bar{e}^{(p)} = \sqrt{\tfrac{2}{3}}(de_{ij}^{(p)}\, de_{ij}^{(p)})^{\frac{1}{2}} \qquad \text{..............2.4}$$

where $de_{ij}^{(p)}$ are the components of the deviatoric plastic strain increment, noting that for no plastic volume change,

$$de_{ii}^{(p)} = 0 \qquad \text{..............2.5}$$

As the generalized or equivalent stress (in this case the uni-axial yield stress in compression) is given by

$$\bar{\sigma} = \sqrt{\tfrac{3}{2}}(\sigma_{ij}'\, \sigma_{ij}')^{\frac{1}{2}}, \qquad \text{..............2.6}$$

It can be shown that

$$W_p = \int_0^{\bar{e}^{(p)}} \bar{\sigma}\, d\bar{e}^{(p)} \qquad \text{..............2.7}$$

It can easily be shown that the actual work per unit volume performed on an element of material extruded hydraulically is equal to the pressure of the extruding fluid, so that

$$W_p = p \qquad \text{..............2.8}$$

Equations 2.1 and 2.7 result in

$$\bar{\sigma} = H\int d\bar{e}^{(p)} \qquad \text{..............2.9}$$

For the Mises criterion, $\bar{\sigma}$ is a function of the total plastic strain. For uni-axial compression, $\int d\bar{e}^{(p)}$ reduces to the logarithmic strain, and the function H is given by the stress-logarithmic strain curve obtained from the compression test.

For a non-hardening material,

$$W_p = Y\,\bar{e}^{(p)} \qquad \text{..............2.10}$$

$$= p\text{, the fluid pressure.}$$

2.2 The Definition of Extrusion Efficiency

The work per unit volume for an axially symmetric extrusion process for a work-hardening material approaches

$$W_I = \int_0^{\ln\frac{1}{1-r}} \bar{\sigma}\, d\bar{e}^{(p)} \qquad \text{.............2.11}$$

using smooth tapered dies, as the semi-angle of the dies approaches zero (10). In this ideal process, the billet undergoes homogeneous deformation. For a non-hardening material, this ideal work per unit volume is

$$W_I = Y \ln \frac{1}{1-r} \qquad \text{.............2.12}$$

The extrusion efficiency (11) is defined as the ratio of the ideal work per unit volume to the actual work per unit volume and is given by

$$\eta = \frac{W_I}{W_P} = \frac{W_I}{P} \qquad \text{.............2.13}$$

CHAPTER III

BOUNDS FOR THE HYDRAULIC EXTRUSION PROCESS

In an ideal process, there is neither friction nor redundant shearing. For a non-hardening material, equation 2.12 gives the fluid pressure required to extrude hydraulically if there is no redundant shearing. Restated, this is

$$p = Y \ln \frac{1}{1-r} \qquad \text{.............3.1}$$

The pressure required to extrude a work-hardening material for the ideal process is given by

$$p = \int_0^{\ln \frac{1}{1-r}} \bar{\sigma} \, d\bar{e}.^{(p)} \qquad \text{.............3.2}$$

These pressures are lower bounds for the hydraulic extrusion process. These are not close lower bounds, however, because the actual strain paths of the elements differ greatly from those of homogeneous deformation. There is, actually, considerable redundant shearing and considerable friction at the die.

3.1 Use of the Inverted Mechanical Extrusion Process as an Upper Bound

If a solution is based on a kinematically admissible velocity field, then this solution gives an upper bound for the load required (12). If this solution has an associated statically admissible stress field that can be extended into the non-deforming region, the load is a lower bound also and is exact (13). The solution is then a complete one.

Alexander (14) indicates the complete solution of a plane strain mechanical extrusion problem with a frictionless die by extending the stress field into the non-deforming region. If the velocity field of

this solution is used for the plane strain analogue of the hydraulic extrusion process, it is kinematically admissible. The loads for the mechanical extrusion process are therefore upper bounds for the hydraulic extrusion process using frictionless dies with the same die angles. It is reasonable to expect that the theoretical loads for the mechanical extrusion process are upper bounds for the loads for the hydraulic extrusion process.

CHAPTER IV

APPARATUS AND MATERIAL

All loads were applied using a 400,000 pound Tinius Olsen testing machine.

4.1 Hydraulic Extrusion Apparatus

The apparatus used for hydraulic extrusion is illustrated in figure 1.

The sleeve and container were both of medium carbon steel, with respective bore sizes of 2.125 and 2.000 inches. The bore of the sleeve had a honed finish.

Sealing between the medium carbon steel piston and the sleeve was accomplished by means of six rubber o-rings.

There were annealed copper seals between the container and sleeve and between the container and die support. Sealing was assured by tightening the high strength bolts uniformly with a torque wrench.

The dies were of hardened Keewatin steel and had a ground finish. The dies had semi-angles of thirty degrees and forty-five degrees and had an orifice diameter of one half inch.

A Marsh pressure gage, with a capacity of 20,000 pounds per square inch, was used to measure fluid pressure.

A light gear oil, Shell Tellus 27, was used as the extruding fluid for most of the hydraulic extrusion experiments. In addition, some tests were performed using S.A.E. 80 hypoid oil as the extruding fluid.

Shell Alvania 2 grease was used to seal the surface between the

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die and die support. This grease was also packed between the billet and die before each test to lubricate as well as seal.

Tipping of the billet, which occurred occasionally as the extrusion progressed, was prevented by inserting brass collars which surrounded the billet. The internal diameter of each brass collar was about 0.15 inches larger than the external diameter of its corresponding billet.

A two inch travel dial gage was used to measure ram movement.

Because of the large force resulting from the friction of the o-rings, a special device was required to remove the piston from the sleeve after each test. This is illustrated in figure 3.

4.2 Inverted Mechanical Extrusion Apparatus

The features of the inverted mechanical extrusion apparatus are shown in figure 2.

The medium carbon steel container had a honed bore of 1.997 inches.

The dies for mechanical extrusion were of hardened Keewatin steel, 1.995 inches in diameter with conical semi-angles of forty-five degrees.

4.3 Billet Preparation

Billets for both extrusion processes were prepared the same way.

The 0.065 per cent tellurium lead was taken from 4 x 4 x 17 inch long cast billets. From these, smaller blocks of 2 x 2 x 4 inches long were cut. These smaller billets were fully cold-worked at room temperature. Because the recrystallization temperature of 0.065 per cent tellurium lead is 120° C. (15), the cold-working was expected to break up

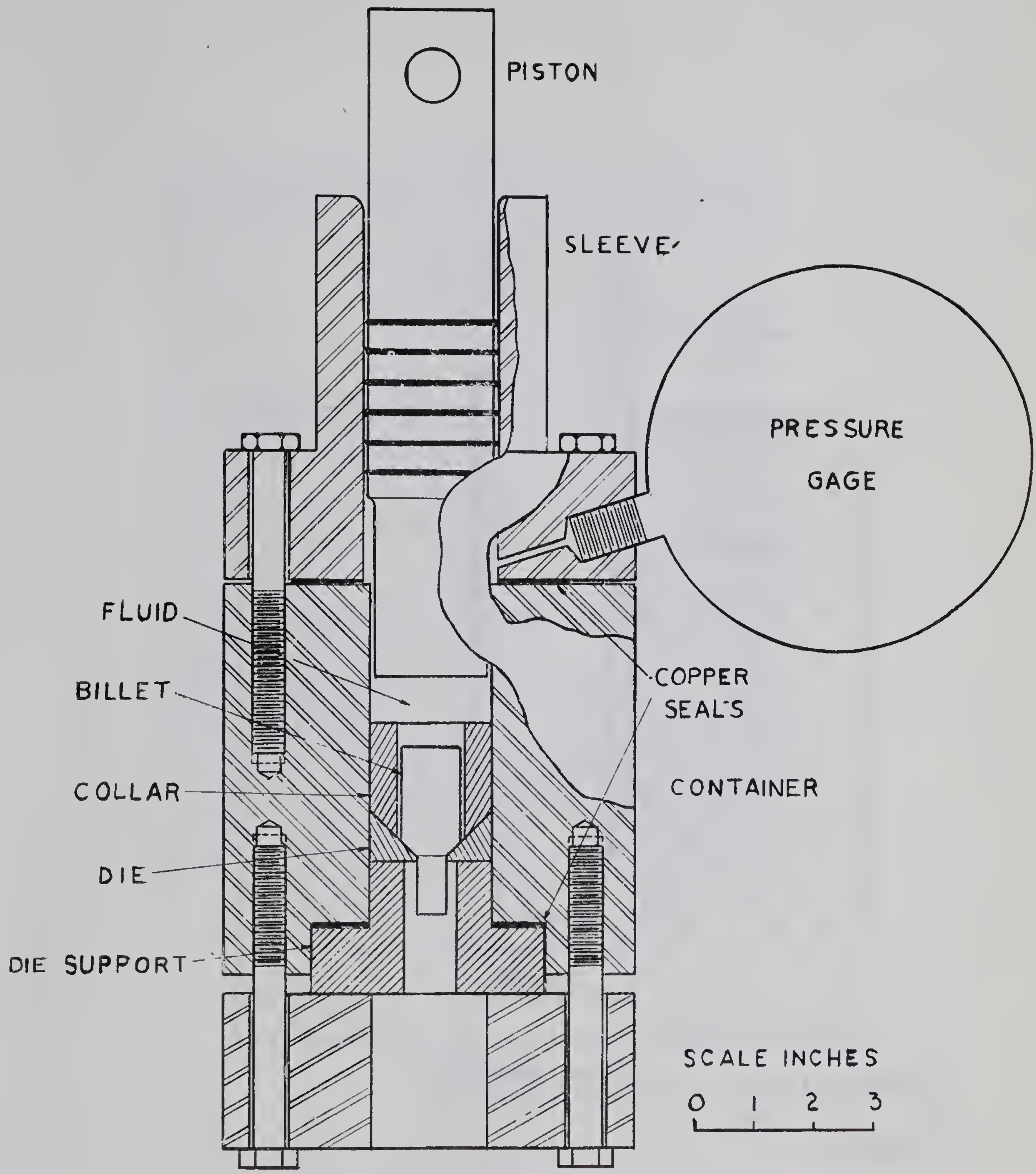

FIGURE 1

HYDRAULIC EXTRUSION APPARATUS

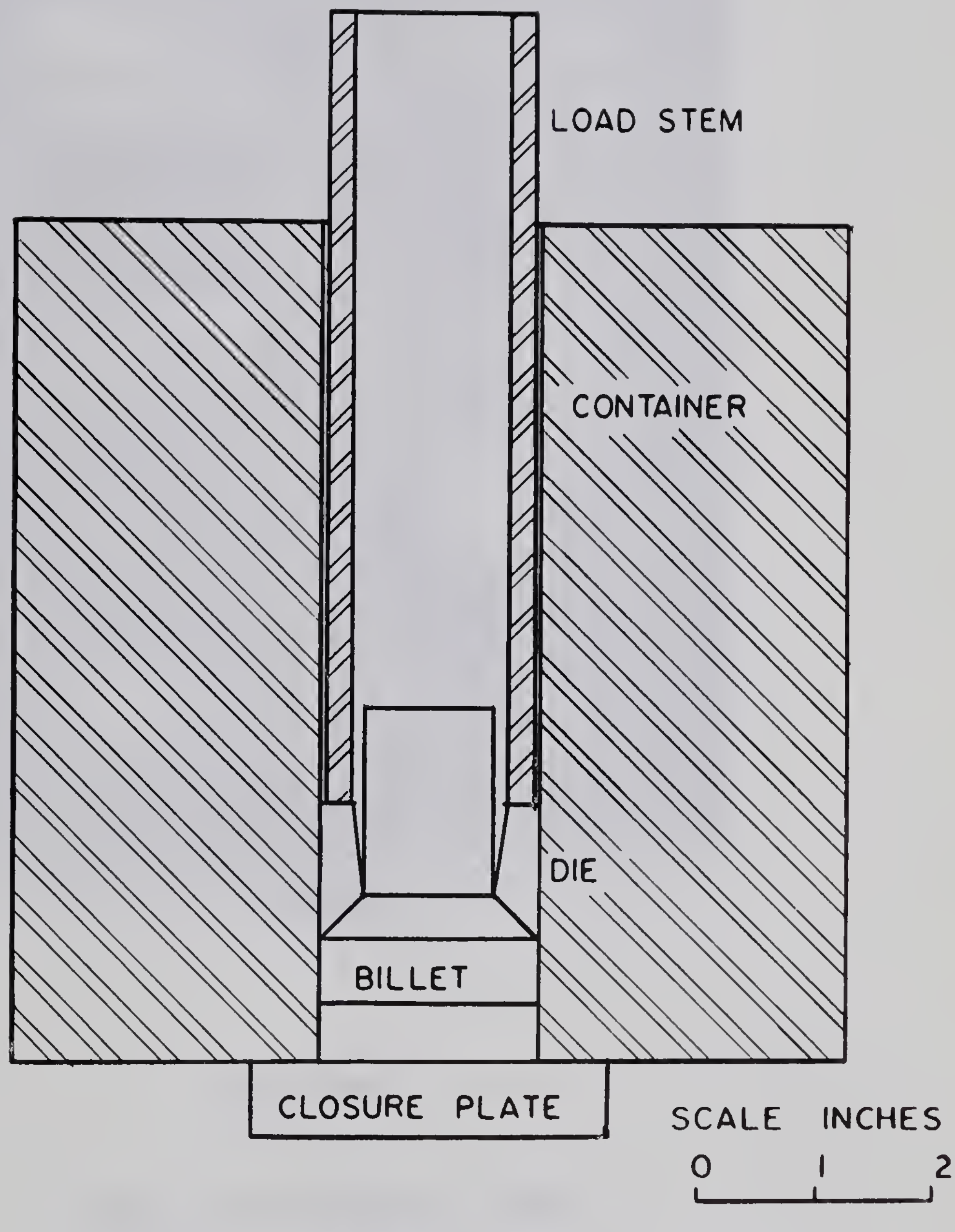

FIGURE 2

INVERTED MECHANICAL EXTRUSION APPARATUS

FIGURE 3

DEVICE FOR REMOVING PISTON

the original cast grain structure.

The billets used for tests on work-hardening material were further prepared by annealing at 220°C. for two hours.

Billets that were not annealed were prepared individually. Billets that were annealed were prepared in quantities of about five.

After the above preparation was completed, the billets were turned down on a lathe to the proper diameters. A cone was machined at one end of the billet so that it could form a good seal when placed in the die.

CHAPTER V

THE STRESS - STRAIN COMPRESSION TEST

The compression test determines a relationship between the uni-axial yield stress and the logarithmic strain for a process in which a cylindrical billet undergoes homogeneous deformation.

Generally, the work per unit volume performed on a cylindrical rod in tension or compression is given by

$$W_p = \int \bar{\sigma}\left(\frac{dl}{l} - \frac{d\bar{\sigma}}{E}\right) \qquad \ldots\ldots\ldots\ldots\ldots 5.1$$

where the elastic work is subtracted (16).

More specifically, for the compression test, where the elastic work is neglected, the work per unit volume is

$$W_p = \int_{l_o}^{l} \bar{\sigma}\, d\left(\ln \frac{l_o}{l}\right) = \bar{\sigma} \ln \frac{l_o}{l} \qquad \ldots\ldots\ldots\ldots\ldots 5.2$$

where l_o is the original length, l is the current length of the test specimen and $\bar{\sigma}$ is the current uni-axial yield stress. It will be shown later in this chapter why the elastic portion of the work is neglected.

By using two lubricated compression platens to compress the specimen, homogeneous deformation is approached. If barreling of the specimen does occur, the billet is turned down on a lathe and compression is resumed.

5.1 Compression Test Procedure

The initial dimensions of the compression specimens were approximately 1.5 inches in height and 1.0 inches in diameter. The specimens

were compressed in the sub-press illustrated in figure 4.

The platens were made of hardened Keewatin steel and were lapped to a smooth finish. The compression platens were lubricated with vaseline before each successive load was applied. The load was applied in increments, each load being about 300 pounds higher than the previous load. The load was released immediately after its application. The specimen was removed from the sub-press after each increment of load was applied and the length was measured using a micrometer. In this way, the elastic strain was neglected. The average cross-sectional area was then obtained.

After a number of loads was applied, slight barreling of the billet became evident. The specimen was then turned down on a lathe and compression was resumed. It was observed that after each machining, the billet was strained plastically before the stress previously obtained was approached. That is, the new stress-strain curve was slightly rounded.

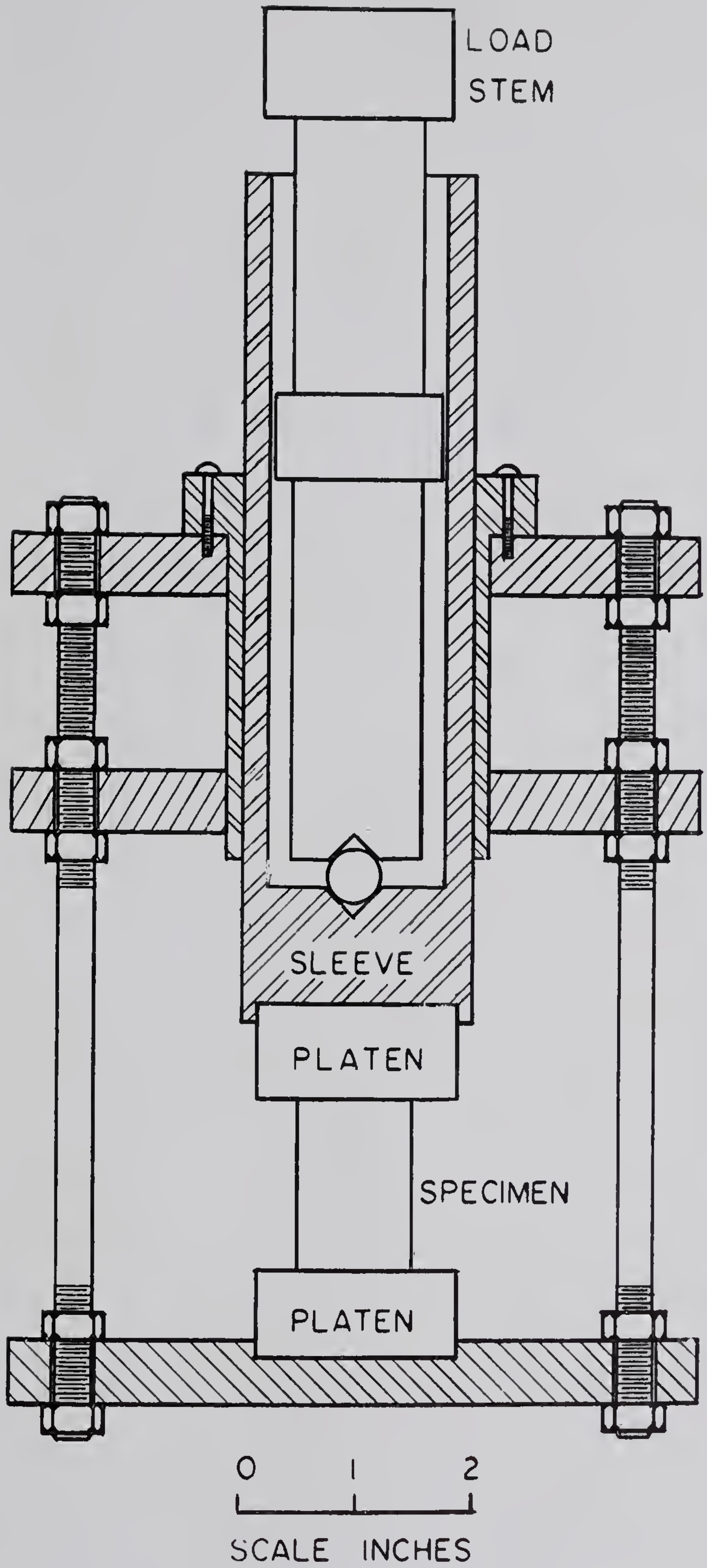

FIGURE 4

COMPRESSION SUB-PRESS

CHAPTER VI

EXPERIMENTAL PROCEDURE

6.1 Hydraulic Extrusion Procedure

With the billet in position, the container was filled with fluid to approximately the level of the copper seal. The piston was then inserted in the sleeve and forced downward. All hydraulic extrusion tests were run at a piston speed of about 0.006 inches per second. Assuming no leakage of fluid, the billet speed was equal to the ratio of the sleeve area to the original billet area multiplied by the piston speed.*

The steady state extrusion pressure was recorded for each test. In addition, the steady state load was recorded from the testing machine dial for each test so that the magnitude of the friction load of the piston could be determined.

For most extrusions, the billet was completely discharged from the container. However, occasionally, extrusions were not complete. The billets that were not completely extruded were removed from the die by cutting through the product near the face of the die.

After each extrusion, the piston was removed from the sleeve using the device shown in figure 3.

* Usually, for mechanical extrusion, when consideration is given to extrusion speed, the speed considered is that of the billet with respect to the die i.e. the speed of the die for inverted mechanical extrusion. Similarly, the speed of the billet is determined for hydraulic extrusion.

6.2 Problems Encountered in Hydraulic Extrusion

6.2.1 For low reduction extrusions, considerable difficulty was encountered in obtaining a steady state extrusion pressure. This is attributed to the elasticity of the system and is due primarily to the compressibility of the fluid (17), which causes a stop-start motion of the billet. Continual fluctuation of the fluid pressure results. This problem was almost completely eliminated by decreasing the volume of fluid in the container.

6.2.2 Without the use of brass collars, tipping of the billet occasionally occurred. This, in effect, increased the cross-sectional area of the billet, which increased the pressure required to extrude the billet. This was overcome by introducing the brass collars between the billet and container wall. The internal diameter of each collar was about 0.15 inches larger than the external diameter of the billet extruded. In addition to making the extrusion pressures more consistent, the insertion of the brass collars resulted in improved straightness of the extruded products.

6.2.3 As each extrusion was completed, the product was discharged violently, usually bending the product, destroying its finish. This problem was not overcome.

6.2.4 Unfortunately, a method was not devised to measure the rate of extrusion of the product accurately. An approximation of the billet speed was obtained from the rate of fluid displacement determined by the piston speed, assuming no fluid losses.

6.3 Inverted Mechanical Extrusion Procedure

Mechanical extrusion tests were performed both with and without lubrication. All tests for the first two series were run at a die speed of 0.006 inches per second using a forty-five degree semi-angle die. For the tests performed using lubrication, Alvania 2 grease was used to cover the billet and die before each test. For the tests performed without lubrication, the billet, die and container bore were washed with acetone before each test.

It was necessary, after each test, to cut through the product near the die face to remove the billet from the die.

A third series of mechanical extrusion tests was performed at various extrusion speeds. Die speeds of 0.002 inches per second to 0.085 inches per second were used to determine the effect of extrusion speed on pressure for low-rate extrusion of 0.065 per cent tellurium lead.

CHAPTER VII

EXPERIMENTAL RESULTS AND DISCUSSION

Tests were conducted on 0.065 per cent tellurium lead which contained 0.02 per cent copper and 0.02 per cent arsenic. The material had a Vickers hardness number of 9.7 for the fully hardened state and 7.1 for the annealed state. The hardnesses were determined by a Leitz microhardness tester using a 100 gram load. Comparison of extrusion efficiencies is made to those obtained by Haddow and Chudobiak (18) who used 0.06 per cent tellurium lead which had Vickers hardness numbers of 8.1 for the fully hardened state and 5.4 for the annealed state.

7.1 The Compression Tests

Figure 5 indicates the variation of true stress with logarithmic strain obtained from the compression tests of annealed and fully hardened tellurium lead.

The compression test was terminated after a logarithmic strain of about 1.1 in each case because the compression specimen was becoming quite short. At this point, a well defined saturation stress had been obtained for the fully hardened lead. For the annealed lead, the work hardening rate became negligible at a logarithmic strain of about 1.0.

It was found that the uni-axial yield stress for annealed tellurium lead did not closely approach the uni-axial yield stress for fully hardened lead. This particular result was also observed by Haddow and

Chudobiak (19).

The saturation yield stress obtained for the fully hardened tellurium lead was 5070 pounds per square inch. The uni-axial yield stress for annealed tellurium lead was determined to be 3830 pounds per square inch.

7.2 The Effect of Extrusion Speed on Pressure for Mechanical Extrusion

Frisch and Thomsen (20) have shown experimentally that for low rates of inverted mechanical extrusion of pure lead, the load required does not vary appreciably. Tests were conducted using square dies for a reduction of 88 per cent at speeds varying from five inches per minute to forty-five inches per minute.

Figure 6 indicates the experimental relationship between billet pressure and extrusion speed for inverted mechanical extrusion of 0.065 per cent tellurium lead. Tests were conducted using forty-five degree semi-angle dies lubricated with Alvania 2 grease for an 86 per cent reduction. The graphical relationship between pressure and extrusion speed is linear. Table I shows the actual billet speeds for the hydraulic extrusion tests for a piston speed of 0.006 inches per second.

For extrusions using forty-five degree semi-angle dies, the inverted mechanical extrusion pressure is compared to the hydraulic extrusion pressure later in this chapter. The errors resulting from comparison of the extrusion processes in which extrusions were conducted at different speeds are obtained from figure 6. This error varies linearly from about

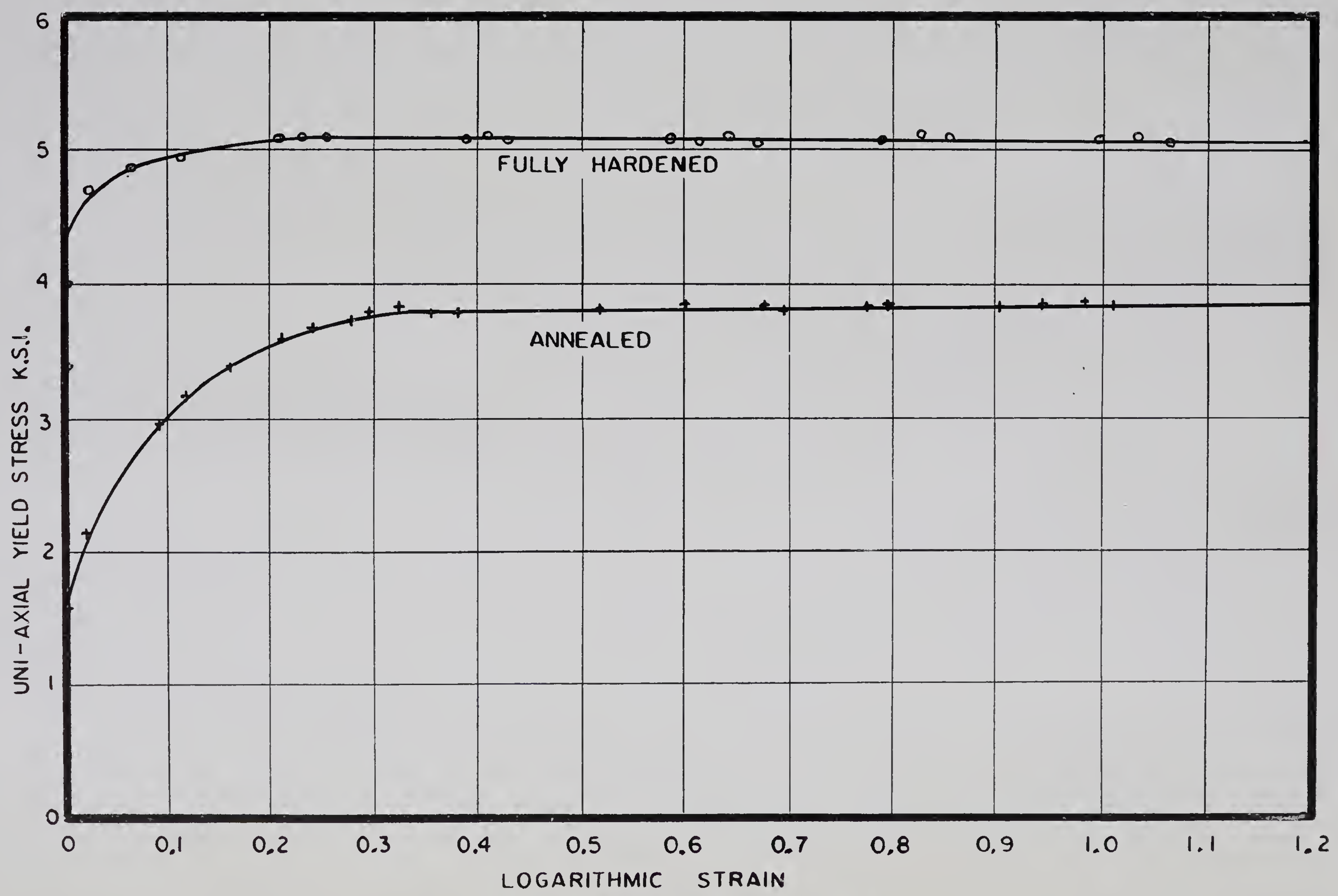

FIGURE 5 STRESS-STRAIN DIAGRAMS

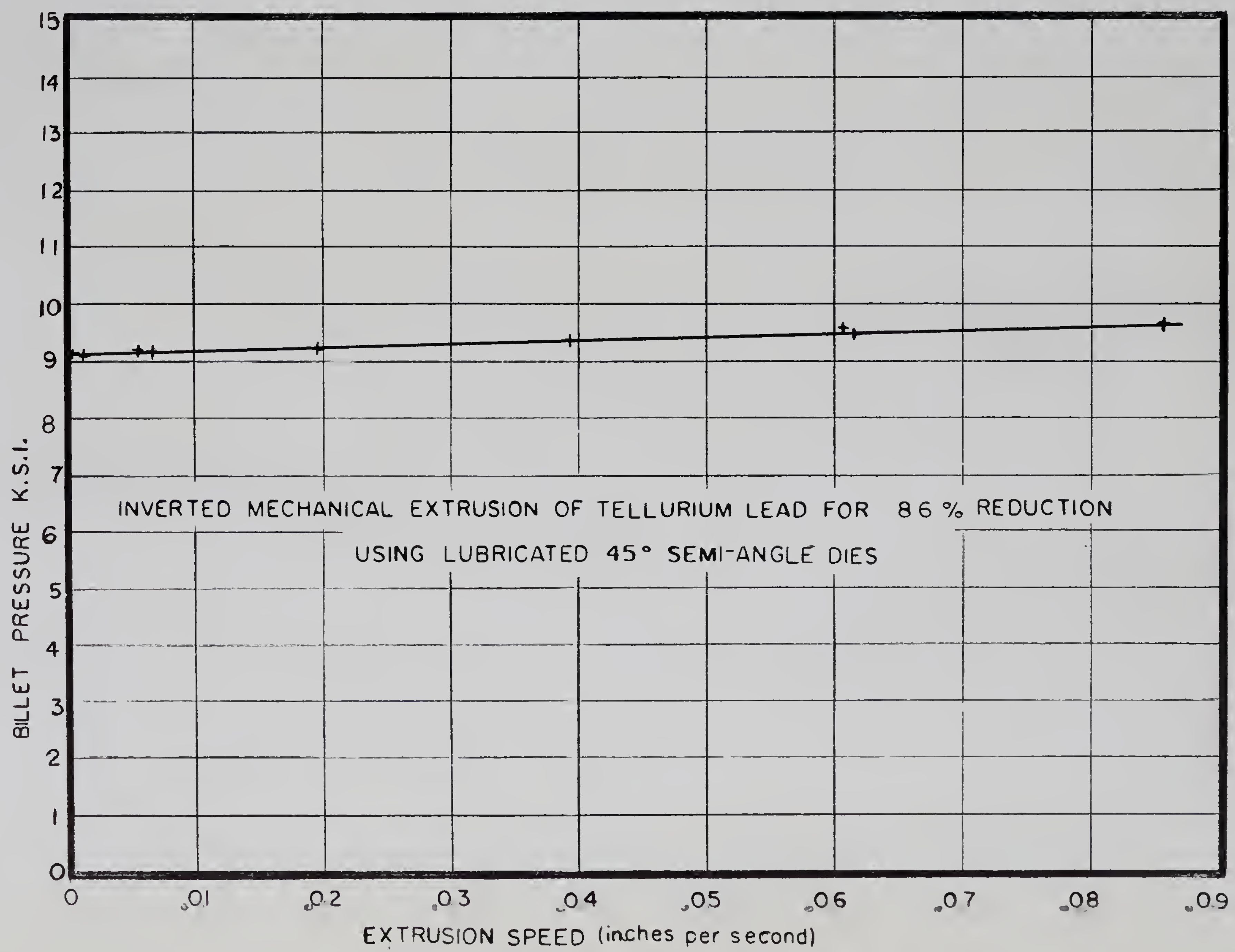

FIGURE 6 **EFFECT OF EXTRUSION SPEED ON PRESSURE**

TABLE I

HYDRAULIC EXTRUSION BILLET SPEEDS FOR PISTON SPEED OF 0.006 INCHES PER SECOND

Per Cent Reduction	Extrusion Speed (in./sec.)
25	0.084
35	0.070
45	0.060
55	0.048
65	0.038
75	0.027
85	0.016
90	0.011

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0.5 per cent for the 90 per cent reduction to about 4.5 per cent for the 25 per cent reduction. It is shown later that this error does not affect the results of the tests.

7.3 Fluid Pressures for Hydraulic Extrusion

It was observed that the fluid pressure obtained from the pressure gage was less than the pressure determined by dividing the testing machine load by the sleeve area by about 200 pounds per square inch for all hydraulic extrusions. There was no discernible variation in friction load at the O-rings with varying steady state fluid pressure. The force required to overcome friction of the o-rings was about 700 pounds.

Steady state pressures were obtained for all hydraulic extrusions. For the greater area reductions of annealed lead, the steady state pressure occurred after an instantaneous maximum pressure. The pressure then dropped slighty from this maximum to a well defined steady state. The maximum pressure exceeded the steady state pressure by about 400 pounds per square inch for a 90 per cent reduction of area. For the annealed material, the difference between maximum fluid pressure and steady state fluid pressure decreased with decreasing reduction to the point where it was not discernible for reductions less than 55 per cent.

For the fully hardened lead, the difference between maximum pressure and steady state pressure decreased from about 800 pounds per square inch for the 90 per cent reduction to about 150 pounds per square inch for the 25 per cent reduction. This decrease in pressure was possibly due to a softening of the material caused by a rise in temperature

resulting from the heat generated in deforming the billet (21).

7.4 The Extruded Products

Figures 7 and 8 illustrate various hydraulic extrusion products. In figure 8, all extrusion products shown were not extruded completely. For items 1 to 5, the process was stopped deliberately before the extrusion was completed. Items 6 and 7 were extruded in the normal manner, but near the end of the extrusion, propagation of the cavity past the die orifice resulted in a shear failure of the specimen. This caused a separation of the product from the portion of the billet not yet extruded. This indicates that there is considerable friction between the billet and die.

All the products shown in figure 8 were completely extruded. Note the deformation of these products caused by their violent expulsion from the container. Figure 9 shows cavity formation for hydraulic extrusion products completely discharged from the container. Items 16 to 19 are fully hardened lead. Items 20 to 23 are of annealed lead.

7.5 Pressure - Reduction Diagrams

Figures 12, 13 and 14 illustrate the experimentally determined relationships between extrusion pressure and percentage reduction. Fluid pressures obtained from the pressure gage are the pressures plotted for hydraulic extrusion. For inverted mechanical extrusion, the pressure plotted is that obtained by dividing the ram load by the billet cross-sectional area. All pressures recorded are steady state pressures.

Also shown on figures 12 and 13 are the lower bounds obtained from

FIGURE 7

INCOMPLETE HYDRAULIC EXTRUSION PRODUCTS

FIGURE 8

COMPLETE HYDRAULIC EXTRUSION PRODUCTS

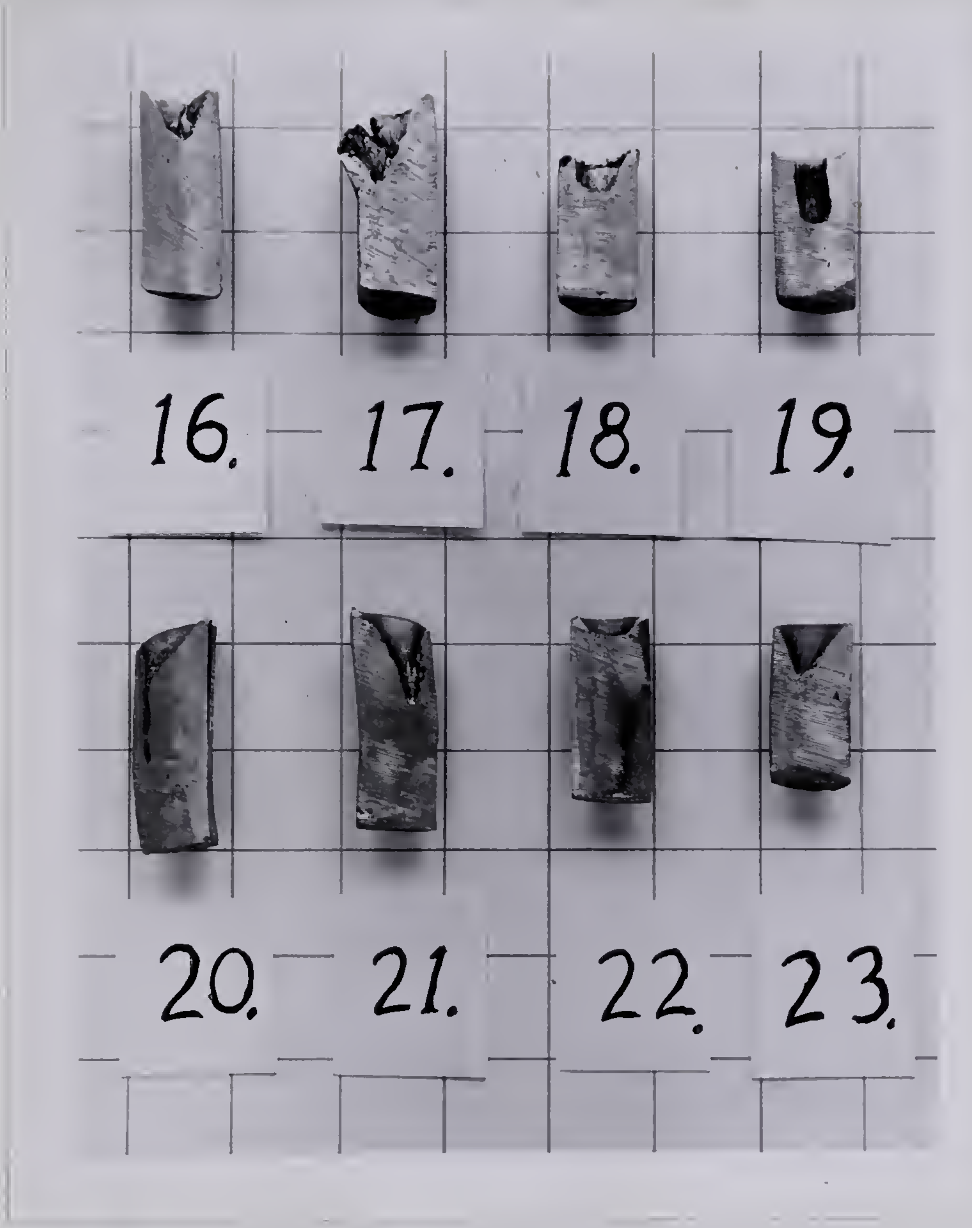


FIGURE 9

CAVITY FORMATION FOR HYDRAULIC EXTRUSION

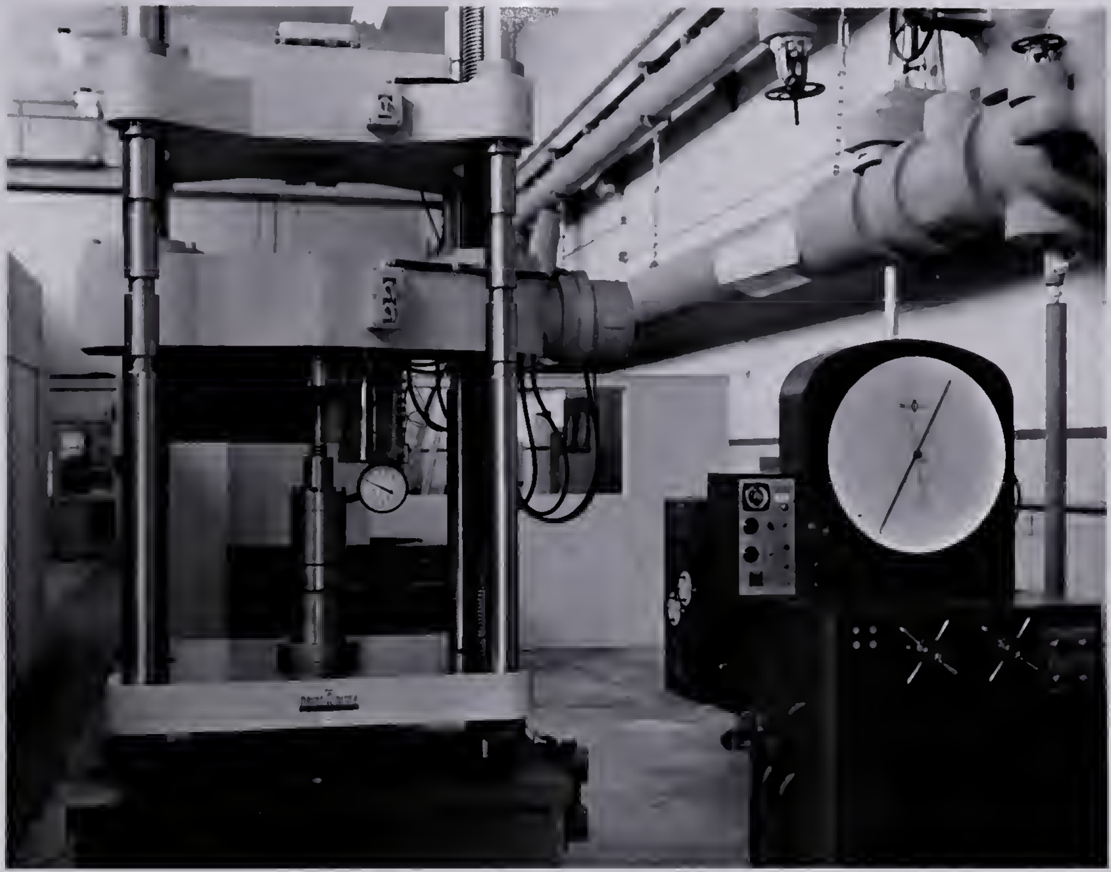


FIGURE 10 HYDRAULIC EXTRUSION APPARATUS IN TESTING MACHINE

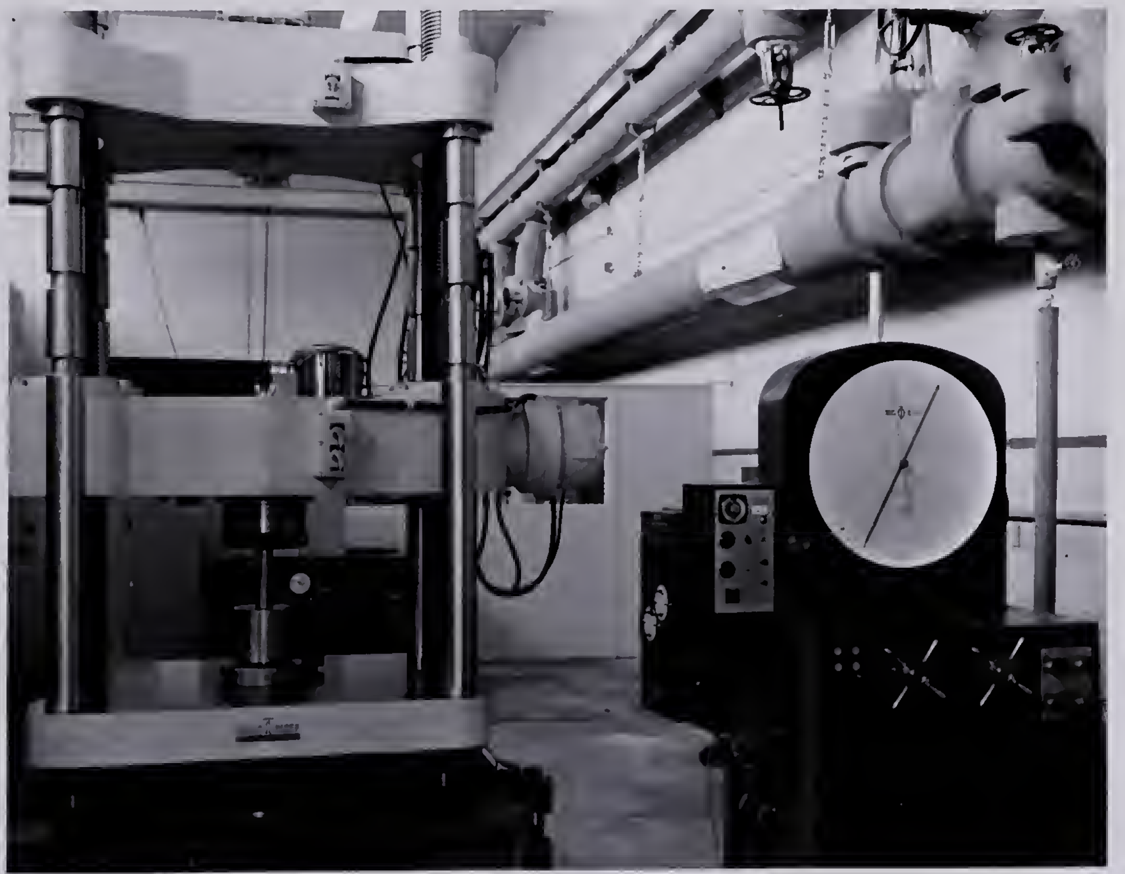


FIGURE 11 INVERTED MECHANICAL EXTRUSION APPARATUS IN TESTING MACHINE

the ideal extrusion process where homogeneous deformation is assumed. Note that this is a very low lower bound for the entire range of reductions. The results shown in figure 14 are very significant. Lubricated inverted mechanical extrusion requires a lower extrusion pressure than does hydraulic extrusion for the same reduction and die angle (forty-five degrees). It can be seen from figure 14 that neglecting the effect of extrusion speed on extrusion pressure does not account by itself for the fact that the hydraulic extrusion pressure is so much greater than the pressure for inverted mechanical extrusion using lubricated dies. The only other obvious explanation is that the presence of the pressurized fluid for hydraulic extrusion does not ensure lubrication of the billet-die interface. Evidently the hydraulic extrusion process does not possess an inherent advantage whereby the pressurized fluid provides for better lubrication during extrusion, thereby reducing the required extrusion pressure. Rather, it is more important that a good lubricant is used at the billet-die interface, regardless of the process, so that extrusion pressure may be reduced.

Figure 12 shows that extrusion through a thirty degree semi-angle die requires a lower pressure than extrusion through a forty-five degree semi-angle die. Figure 12 also shows that hypoid oil offers better lubrication than light gear oil when using a forty-five degree semi-angle die, but offers no advantage when extruding through a thirty degree semi-angle die. Also, figure 14 shows that non-lubricated inverted mechanical extrusion of annealed lead using forty-five degree semi-angle dies requires an extrusion pressure about 700 pounds per square inch greater than hydraulic extrusion and about 2500 pounds per square inch greater

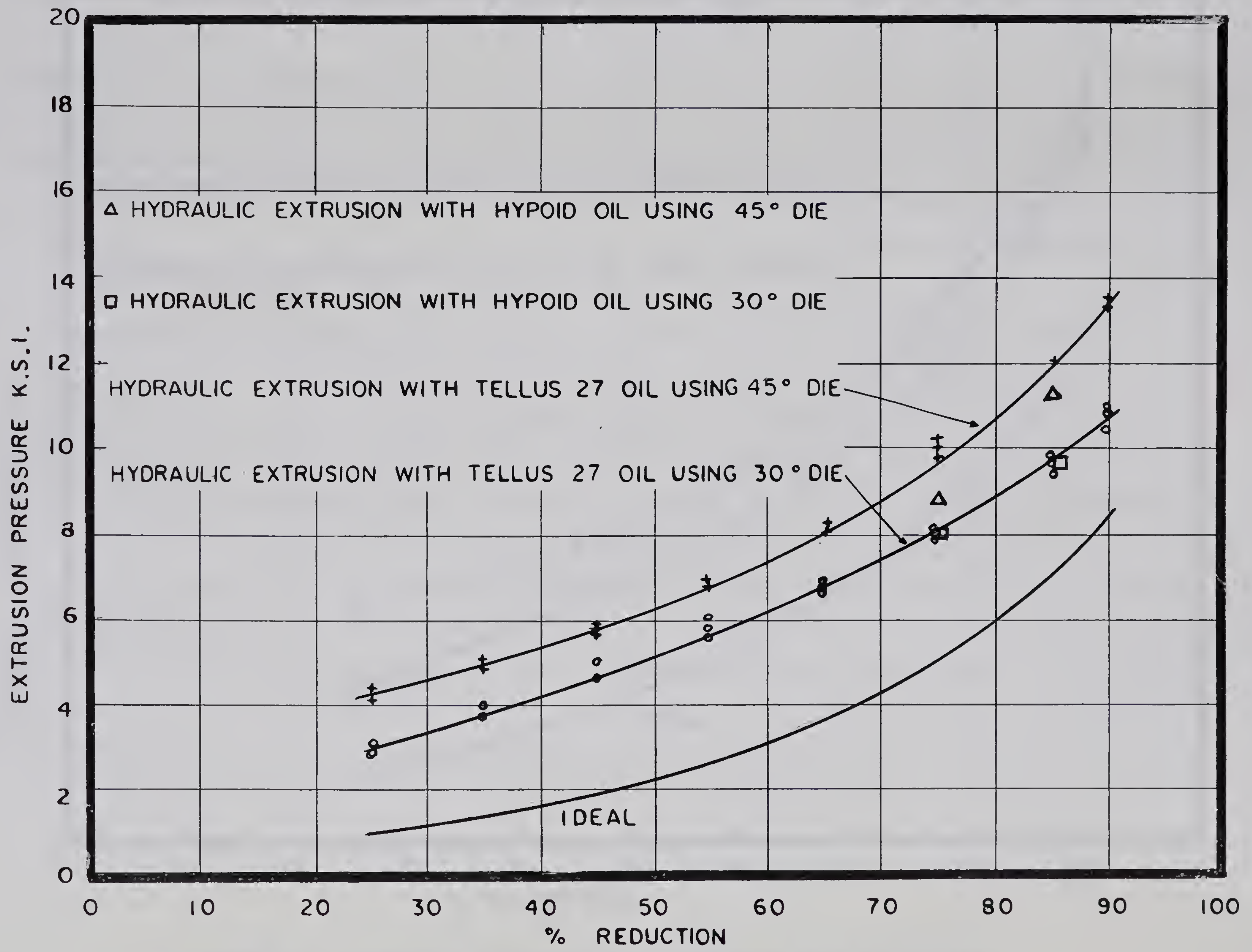
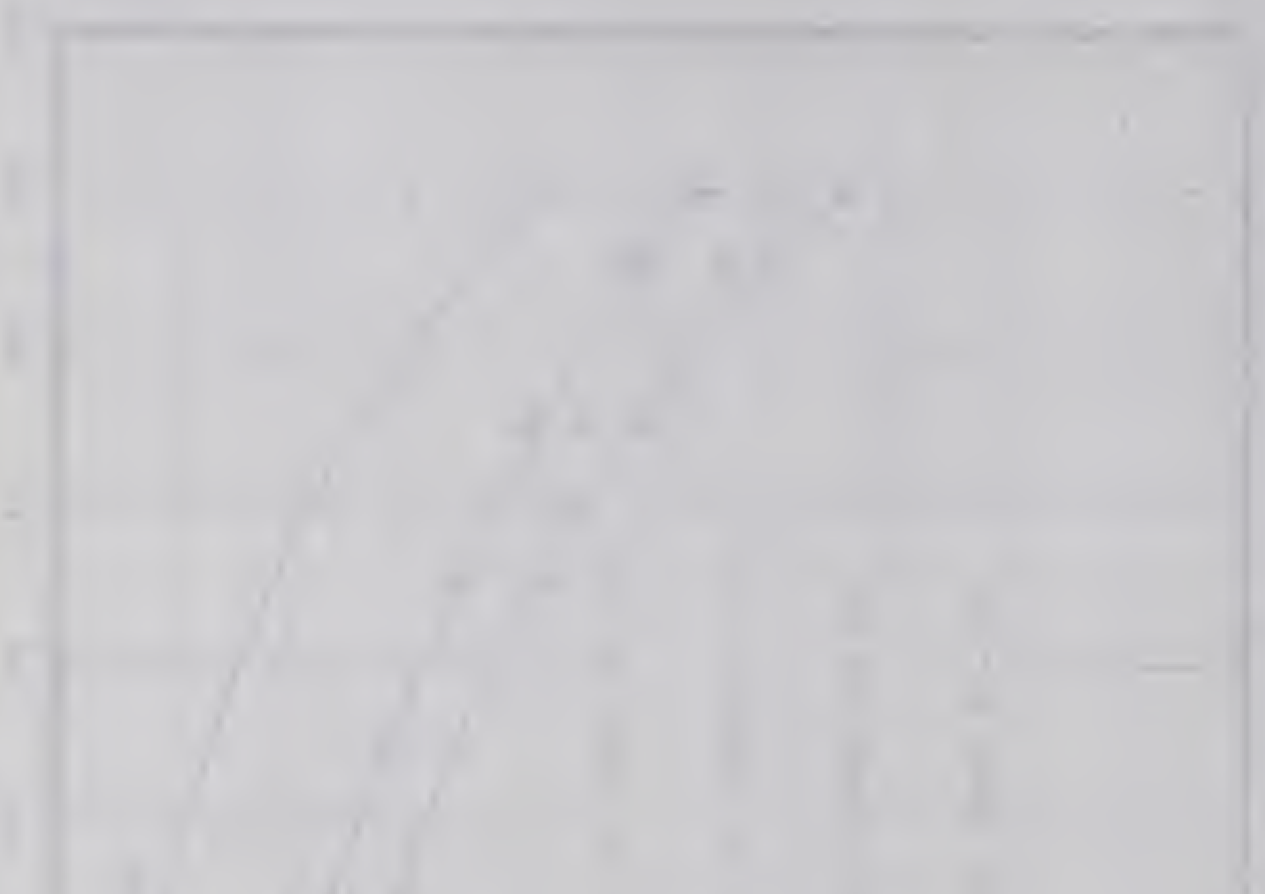


FIGURE 12 EXTRUSION PRESSURE vs. REDUCTION FOR HYDRAULIC EXTRUSION OF ANNEALED TELLURIUM LEAD



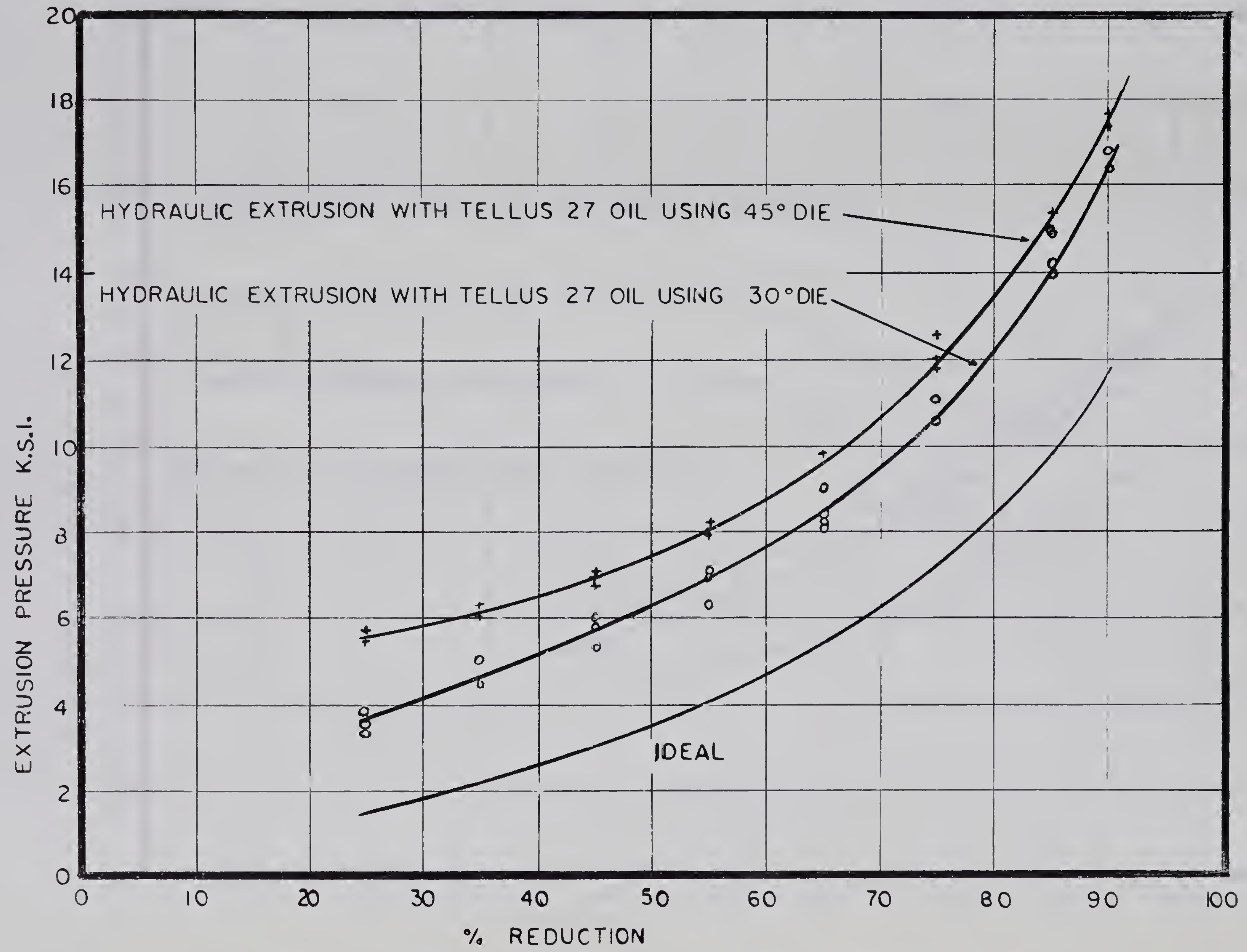


FIGURE 13 EXTRUSION PRESSURE vs. REDUCTION FOR HYDRAULIC EXTRUSION OF NON-HARDENING TELLURIUM LEAD

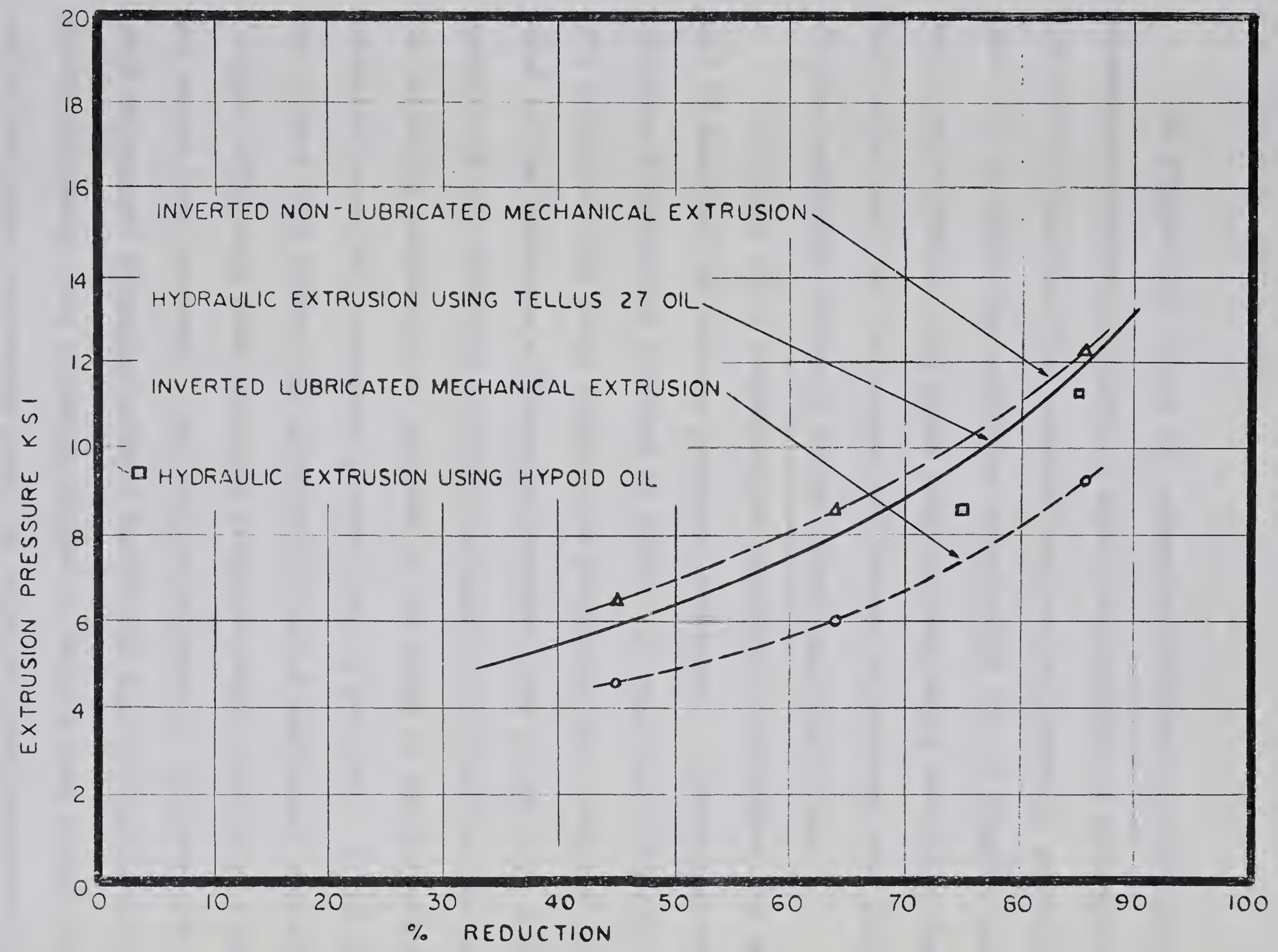


FIGURE 14 EXTRUSION PRESSURE vs. REDUCTION FOR ANNEALED LEAD USING FORTY-FIVE DEGREE SEMI-ANGLE DIES

than lubricated mechanical extrusion.

7.6 Extrusion Efficiencies

In figures 15, 16 and 17, extrusion efficiency is plotted against percentage reduction. Figure 15 shows the variation of extrusion efficiency with reduction for annealed lead for the hydraulic extrusion process. It is shown that extrusion using hypoid oil is slightly more efficent than extrusion using light gear oil when using forty-five degree semi-angle dies, but that hypoid oil offers no advantage over light gear oil when extruding through a thirty degree semi-angle die.

In figure 16, a comparison of extrusion efficiencies for annealed lead is made for the various processes considered. Inverted mechanical extrusion efficiencies obtained by Haddow and Chudobiak (22) for 0.06 per cent tellurium lead using square dies lubricated with vaseline are compared to the extrusion efficiencies obtained from figure 14. A characteristic of the hydraulic extrusion process not evident for the mechanical extrusion process is an increase in the slope of the efficiency-reduction curve for reductions greater than 75 per cent. It is surprising to note that square die inverted lubricated mechanical extrusion has a higher efficiency than hydraulic extrusion where forty-five degree semi-angle dies are used. Also very significant is the fact that lubricated mechanical extrusion using a forty-five degree semi-angle die has a higher efficiency than hydraulic extrusion using either thirty degree or forty-five degree semi-angle dies. As expected, non-lubricated inverted mechanical extrusion has the lowest extrusion efficiency.

Figure 17 shows the experimental relationship between extrusion

efficiency and percentage reduction for fully hardened lead. Hydraulic extrusion using thirty degree semi-angle dies is the most efficient process shown. Hydraulic extrusion using forty-five degree semi-angle dies is more efficient than square die inverted mechanical extrusion for reductions greater than 35 per cent.

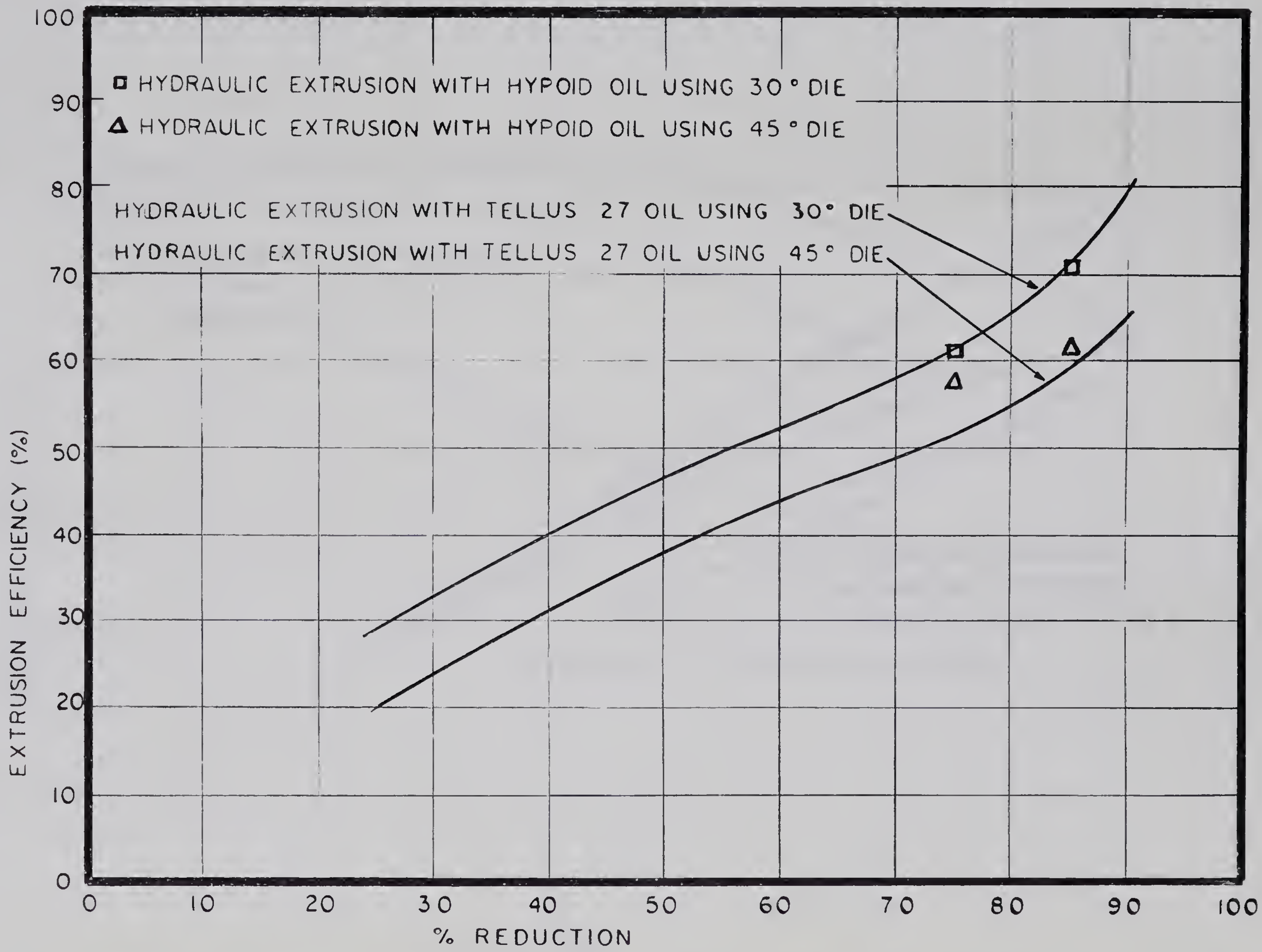


FIGURE 15 EXTRUSION EFFICIENCY vs. REDUCTION FOR HYDRAULIC EXTRUSION OF ANNEALED TELLURIUM LEAD

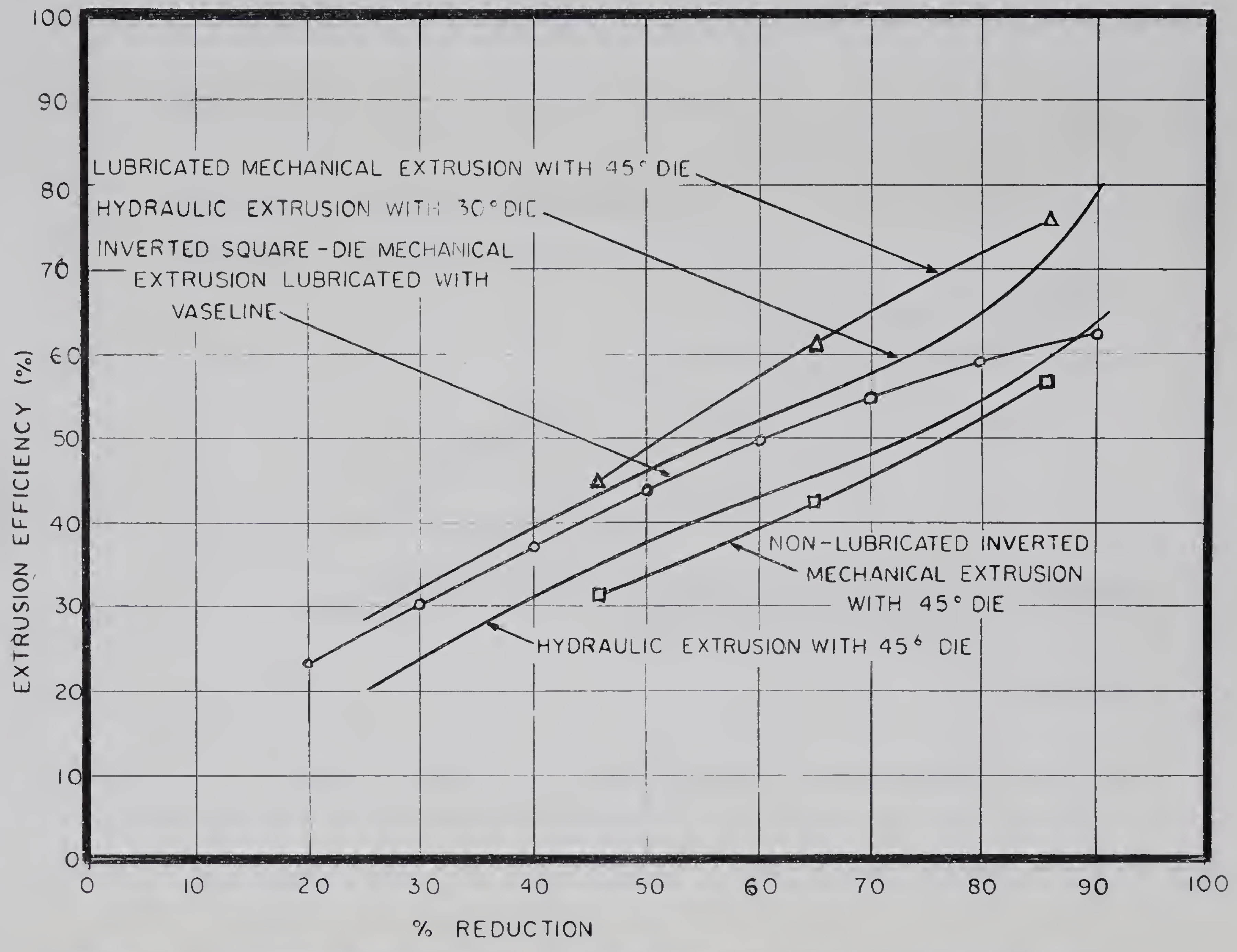


FIGURE 16 EXTRUSION EFFICIENCY vs. REDUCTION FOR ANNEALED TELLURIUM LEAD

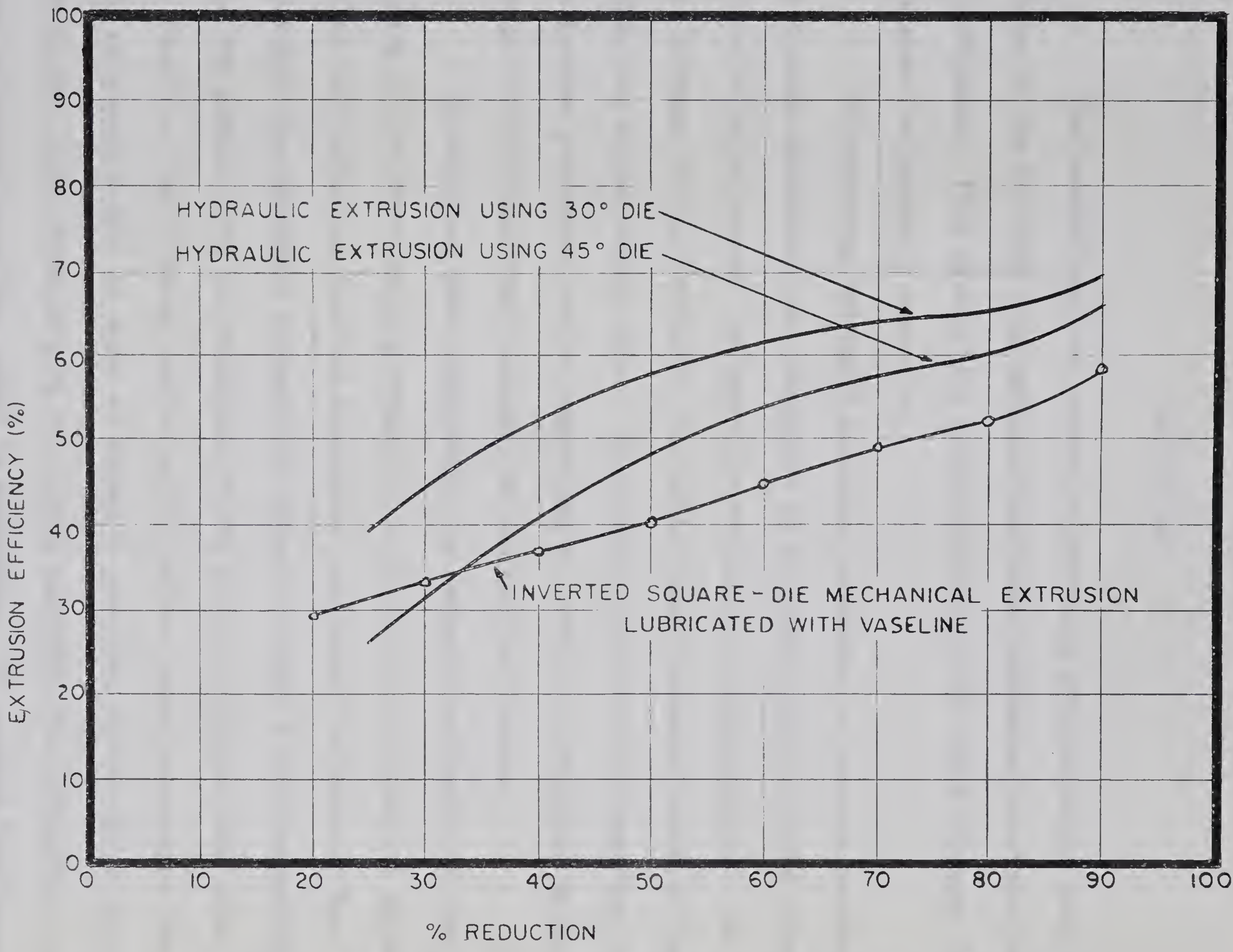


FIGURE 17 EXTRUSION EFFICIENCY vs. REDUCTION FOR NON-HARDENING TELLURIUM LEAD

CHAPTER VIII

CONCLUSIONS

The possibility that hydraulic extrusion permits better lubrication of the die than does inverted lubricated mechanical extrusion is investigated. This possibility arises because of the fluid inherent in the system for hydraulic extrusion.

In comparing hydraulic extrusion pressures to inverted mechanical extrusion pressures, the assumption of no fluid leakage for the calculation of billet speeds for hydraulic extrusion is conservative. That is, if leakage of fluid occurred, the billet speed estimated would be higher than the actual billet speed. As a result, the error in comparing the extrusion pressures, due to neglecting the effect of extrusion speed, would be less than that indicated in the previous chapter.

It was found that lubrication for hydraulic extrusion of lead using oil in the viscosity range S.A.E. 30 to S.A.E. 80 was not better than for lubricated inverted mechanical extrusion. Evidence of die friction for hydraulic extrusion is shown in figure 7 where separation of the product from the remainder of the billet indicates dead metal as a result of die friction when using forty-five degree semi-angle dies. It is possible that in order to attain a good seal at the billet-die interface, the fluid pressure must be of such magnitude that lubrication at the billet-die interface cannot be maintained. It appears that the selection of the lubricant for either process has much more effect on the required pressure than does the selection of the process itself.

Results obtained here disagree with the remarks of Beresnev (23)

who states that extrusion pressures for aluminum were much lower for hydraulic extrusion than for mechanical extrusion. It was stated that this is, in part, due to better lubrication at the die but because direct mechanical extrusion was employed instead of inverted mechanical extrusion, an additional load was required to overcome friction between the billet and container wall. The possibility that the difference in pressure may be due entirely to the friction between the billet and container wall was not considered.

The hydraulic extrusion process does possess the advantage that billets having large length: diameter ratios can be extruded easily. An apparatus that can extrude billets with a large length: diameter ratio would not require the collars to prevent tipping of the billets.

It was found that the lower bound for the extruding pressure was a very low estimate because homogeneous deformation was assumed. The use of the mechanical extrusion pressure as an upper bound was shown to be of limited value because of the effects of the various lubricants. It appears that if duplication of friction conditions could be achieved for both processes, that the mechanical extrusion pressure would be a close upper bound for the hydraulic extrusion pressure.

BIBLIOGRAPHY

1. P.W. Bridgman, "Large Plastic Flow and Fracture", McGraw-Hill, 1952, p. 174.

2. H.Ll.D. Pugh and D.A. Gunn, National Engineering Laboratory Report, M.E.R.L. 31, 1960.

3. H.Ll.D. Pugh and D. Green, National Engineering Laboratory Report, M.E.R.L. 103, 1960.

4. H.Ll.D. Pugh and D. Green, National Engineering Laboratory Report, M.E.R.L. 147, 1960.

5. B.I. Beresnev, L.F. Vereschagin, Y.N. Ryabinin, and L.D. Livshits, "Some Problems of Large Plastic Deformation of Metals at High Pressures", MacMillan, 1963, pp. 24-53.

6. C.S. Cook, R.J. Fiorentino and A.M. Sabroff, "Design Factors for Hydrostatic Extrusion", A.S.M.E., 1964, Paper No. 64-MD-13.

7. D. Green, "An Experimental High Speed Machine for the Practical Exploitation of High Speed Extrusion", Journal of Institute of Metals, vol. 93, 1964, pp. 65-70.

8. P.S. Symonds, "On the General Equations of Axial Symmetry in the Theory of Plasticity", Quarterly Journal of Applied Mathematics, vol. 6, 1949, pp. 448-452.

9. G.I. Taylor and H. Quinney, "The Plastic Distortion of Metals", Philosophical Transactions of the Royal Society of London, A., vol. 230, 1931, p. 323.

10. W. Johnson, "Extrusion Through Wedge-Shaped Dies", Pt. 1, Journal of Mechanics and Physics of Solids, vol. 3, 1955, p. 218.

11. J.B. Haddow, "Ideal Die Pressures for Axially Symmetric Tube Extrusion", International Journal of Mechanical Sciences, vol. 4, 1962 pp. 477-484.

12. R. Hill, "On the State of Stress of a Rigid Plastic Solid", Philosophical Magazine, vol. 42, 1951, p. 868.

13. J.F.W. Bishop, "On the Complete Solution to Problems of Deformation of a Plastic-Rigid Material", Journal of Mechanics and Physics of Solids, vol. 2, 1953, p. 43.

14. J.M. Alexander, "On Complete Solutions for Frictionless Extrusion in Plane Strain", Quarterly of Applied Mathematics, vol. 19, 1961, pp. 31-37.

15. W. Hofmann and H. Hanemann, "Summary of Metallurgical Review", vol. 6, No. 23, 1961, p. 341.

16. R. Hill, "The Mathematical Theory of Plasticity", Oxford University Press, 1950, p. 27.

17. D. Green, op. cit., p. 66.

18. J.B. Haddow and J.M. Chudobiak, "An Experimental Study of Axially Symmetric Inverted Extrusion and Piercing", Canadian Metallurgical Quarterly, vol. 2, No. 4, 1963.

19. Ibid.

20. J. Frisch and E.G. Thomsen. "The Effect of Process Variables on Extrusion Pressures of Lead", Trans. A.S.M.E., ser. B, vol. 81, 1959, p. 207.

21. Research Dept., The Consolidated Mining and Smelting Company of Canada, Limited, "The Lead Industry", 1944, pp. 9-12.

22. J.B. Haddow and J.M. Chudobiak, op. cit.

23. B.I. Beresnev, et al, op. cit., p. 49.

24. W. Johnson and F.W. Travis, "Explosive Hydrodynamic Extrusion of Metals", The Engineer, March 26, 1965, vol. 220, No. 5696.

25. Ibid.

26. Ibid.

APPENDIX

DEVELOPMENT OF EXPLOSIVE HYDRODYNAMIC EXTRUSION APPARATUS

Explosive hydrodynamic extrusion varies from conventional hydraulic extrusion in that the pressure required to extrude the billet results directly from the generation of gases from burning explosive powder in the enclosed container. The expanding gas pressurizes the container, forcing the billet through the die. The cost of high-pressure pumping equipment is eliminated in this way. The term "explosive hydrodynamic extrusion" was first used by Johnson and Travis (24). High speed metal extrusion has been investigated previously, however, it is believed that Johnson and Travis were the first to investigate explosive extrusion.

A. Apparatus

The present stage of the apparatus for explosive hydrodynamic extrusion is shown in figure 18. The container was of mild steel. High strength bolts were used to fasten the supports to the container. Forty-five degree semi-angle dies of hardened Keewatin steel with orifice sizes of 3/4 and 1/2 inch were used for reduction of the metal. The dies had a ground finish. So that the apparatus could be easily dissembled, the cap was made so that it could be fixed in position or taken out of position by rotating it ninety degrees.

The billet-die interface was lubricated with Alvania 2 grease.

The billets extruded in hydrodynamic tests were of cast tellurium lead.

The explosive used was smokeless powder. Using a bomb calormeter,

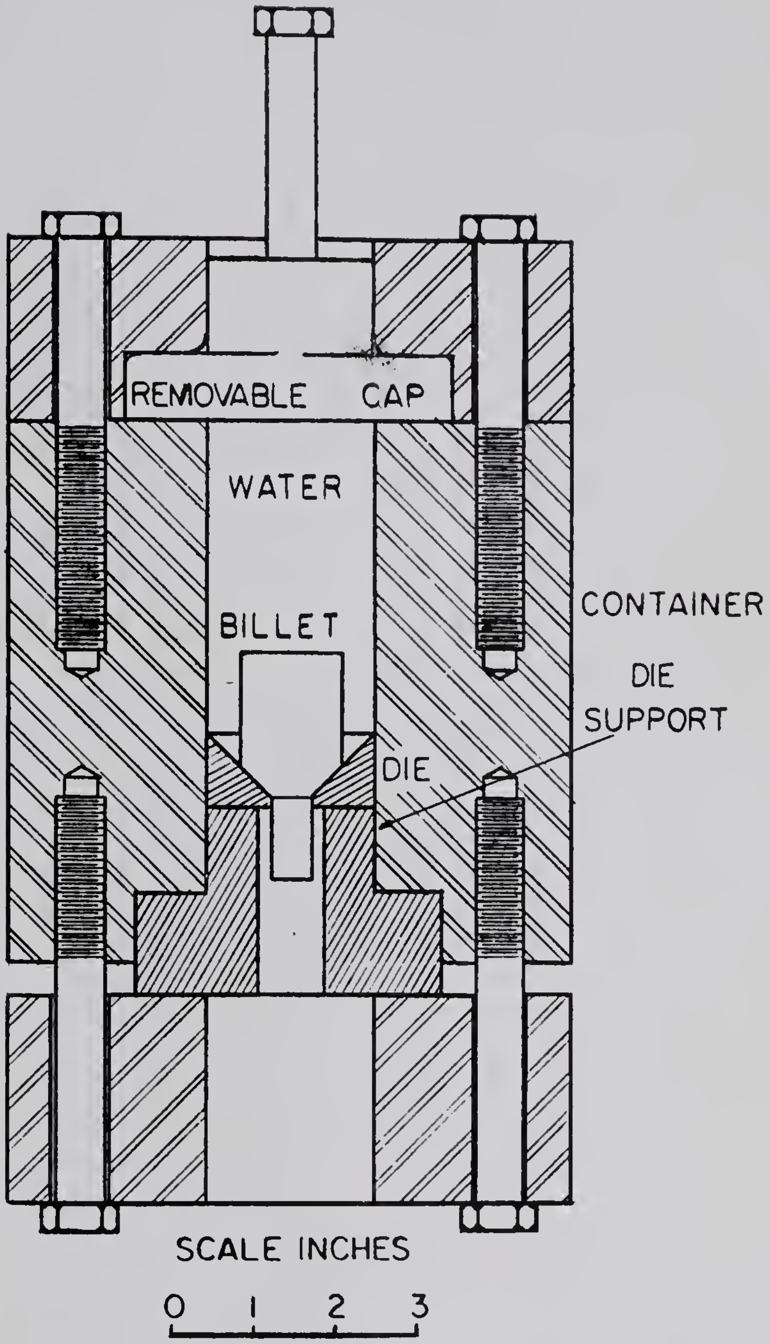


FIGURE 18

EXPLOSIVE HYDRODYNAMIC EXTRUSION APPARATUS

the heating value of the explosive was determined to be about 1220 calories per gram. The explosive was discharged by means of a squib whose heating value was determined to be about 600 calories. For each extrusion, about 10 grams of explosive were sealed with the squib in a rubber balloon.

B. Test Procedure

With the die and billet in place in the container, the container was filled with water. The balloon containing the explosive was positioned at the top of the container. The cap was then put in place. The wires from the explosive were led out through a groove in the cap. The charge was then ignited using a 6-volt dry cell battery.

C. Discussion of Extrusion Products

Typical products are shown in figure 19. Complete extrusions were not obtained for any tests. Separation of the tip of the billet occurred for most extrusions. This separation of the tip of the billet was also encountered by Johnson and Travis (25). Using a high speed camera, they found that the first portion of the product emitted travelled at a velocity of about 200 feet per second whereas the velocity of the remaining extrusion product was about 155 feet per second. The detachment of the tip is a tensile failure resulting from the deceleration of the extrusion process. It is possible that this deceleration results from increased friction at the die caused by expulsion of the lubricant from the face of the die.

It was observed that the surface of the product was very

corrugated and irregular. This is due, in part, to the heat imparted to the metal as a result of the high speed deformation. The rapidity of the extrusion prevents the heat from being conducted away. The metal softens as a result of the heat gained. Johnson and Travis (26) observed good lubrication when extruding with oil. It is possible, in this case, that water can cause the rough surface by being emitted between the billet and die.

D. Discussion

Although the apparatus so far developed for these tests was easily assembled and dissembled, the poor sealing at the top of the container resulted in escape of the pressurized gas. This could be responsible for the incomplete extrusions. It is also possible that extrusions were not completed because the explosive burned too rapidly.

It would be desirable to continue working with this apparatus by attempting to achieve better sealing and also using different explosives and fluids.

FIGURE 19

EXPLOSIVE EXTRUSION PRODUCTS